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3D surface topography of cylinder liner forecasting during plateau honing process

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3D surface topography of cylinder liner forecasting during plateau honing process

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Abstract. Areal surface topographies after plateau honing process were measured. A correlation analysis of surface texture parameters was then carried out. As the results, the following parameters describing plateau honed cylinder 3D surface topography were selected: amplitude Sq, Sz, spatial: Str, Std, hybrid SΔq as well as functional: Spq, Svq and Smq. 3D surface topographies were modeled. The modeled surface topographies were correctly matched to measured ones in 77% of all analyzed cases. The plateau honing experiment was then carried out using an orthogonal selective research plan. Two machining parameters were input variables: coarse honing pressure p_v and plateau honing time t. Chosen cylinder liners texture parameters were output values. As the result of the experiment, regression equations connecting plateau honing process parameters p_v and t with recommended 3D surface topography parameters were obtained. Finally, cylinder liner surface topographies were predicted for various values of machining parameters. Proper matching accuracy of modeled to measured textures was assured in 67% of analyzed cases.

1. Introduction

The surface finish of cylinder bores is one of the most substantial factors influencing the friction, wear and lubrication of co-acting surfaces within the engine. Plateau honing process is commonly applied to receive the specific cylinder surface. The final topography is a result of two last steps in plateau honing process: coarse honing and plateau honing. Randomly generating surface roughness is simple and offers the following advantages: elimination of the hardware and software requirements, decrease of cost and time of experimental investigation. Usually non-Gaussian random surfaces with the desired skew and kurtosis were obtained by transforming the surface of normal ordinate distribution using the Johnson translatory system. Watson and Spedding [1] Uchidate et al. [2] as well as Gu and Huang used ARMA method [3], Hu and Tonder used FFT method [4], Bakolas used NCGM (Non-linear Conjugate Gradient) method [5]. Seong and Peterka [6] used FFT to generate a non-Gaussian pressure time series and so did Kumar and Stathopoulos [7]. Their models can be applied to simulation of non-Gaussian rough surfaces [8]. The method of two-process structure of plateau-honed cylinder liners surface simulation is the other possibility. It relies on the fact that fine part of the surface created during second process (plateau honing) has its characteristic amplitude distribution and a whole system represents transitional topography [9]. An idea of the proposed method (and its possible modifications) is imposition of random surface of Gaussian ordinate distribution (second process) on the base surface (first process).

2. Materials and methods

Work pieces from pearlitic grey cast iron with phosphorous eutectic of 220-260 HB material hardness were taken as samples. Plateau honing process was done using Gehring honing machine of type SZS150.M with NC II control. The HON 15 was the cooling fluid. Honing stones with ceramic binder were applied; for coarse honing: 02 8x10x150 5SGG 150 N10 VCA S5 but for plateau honing: 02 8x10x150 70C 500 15 V Ne. Honing angle was 53^0. As the results of initial investigations, the following variables in plateau honing process were selected: coarse honing pressure p_v and plateau honing time t. Plateau honing pressure p_p was constant during in research (0.8 MPa). Firstly a lot of samples (about 20) were subjected to plateau honing process. Then measurement of areal surface topography was conducted using Talyscan 150 stylus equipment. Measuring area was 2 mm x 2 mm, sampling interval was 5 µm in 2 orthogonal directions. The nominal radius of stylus tip was 2 micrometers. The measurement speed was 2 mm/s. After measurement, the form was removed by polynomial of 3rd level. No digital filtration was used. In order to eliminate highly correlated surface topography parameters, correlation analysis was carried out. As the result of correlation analysis, the set of parameters describing surface topography of plateau honed cylinder liners was selected. Then areal surface topographies after plateau honing were simulated. It was assumed that modeling accuracy was acceptable when the parameters of simulated surface topography were within confidence intervals for average parameters of machined (plateau honed) surfaces.

Secondly, the plateau honing experiment was carried out using orthogonal selective research design. Coarse honing pressure p_v (in the range: 4 – 6.4 MPa) and plateau honing time t (6.3-18.9 s) were input parameters. The experiment was also carried out in other research points than resulting from plan. As the result of experiment, the regression equations connecting plateau honing process parameters p_v and t with recommended surface texture parameters were obtained. Finally, surface profiles were predicted for various values of plateau honing parameters.

The following parameters were analyzed: arithmetical mean height of S-F surface Sa, root-mean-square height Sq, maximum pit height Sv, maximum peak height Sp, maximum height Sz, ten-point height S10z, the emptiness coefficient Sp/Sz, skewness Ssk, kurtosis Sku, surface section height difference corresponding to 20-80% of the material ratio SHtp, root-mean square gradient Sdq, arithmetic mean peak curvature Spc, developed interfacial area ratio Sdr, fractal dimension Sfd, texture aspect ratio Str, auto-correlation length Sal, density of peaks Spd and texture direction Sfd. In addition, the following areal parameters for stratified functional S-F surfaces were analyzed: Sk, Spk, Svk, Smr1 and Smr2 as well as Spq, Svq and Smq (ISO 25178-2).

3. Results and discussion

It was assumed that parameters were strongly correlated when absolute value of the linear correlation coefficient ρ was greater than 0.7. Amplitude parameters were strongly interrelated; especially Sa and Sq parameters. These statistical parameters were highly correlated with the following parameters: Sp, Ssk, Sp/Sz, SHtp, Sdq, Sdr, Spc, Spd, Svi, Sk, Svk and Smr1. However they were not statistically connected with parameters describing maximum surface height. Skewness was inverse proportional to kurtosis. Hybrid parameters Sdq, Spc and Sdr are also highly correlated. From among spatial parameters Str and Sal are independent of other parameters but mutually interrelated. The Std parameter was independent. The parameters Spq, Svq and Smq were mutually independent and also not correlated with the other parameters. Parameters from Rk family (Spk, Sk, Svq, Smr1 and Smr2) were mutually independent. On the basis of presented dependencies it was decided to describe surface topography of plateau honed cylinder liners by height parameters Sq and S10z, spatial parameters Str and Std, hybrid parameter Sdq and functional parameters Spq, Svq and Smq.

Table 1. Correlation coefficients for areal surface topography of cylinders after plateau honing (a)

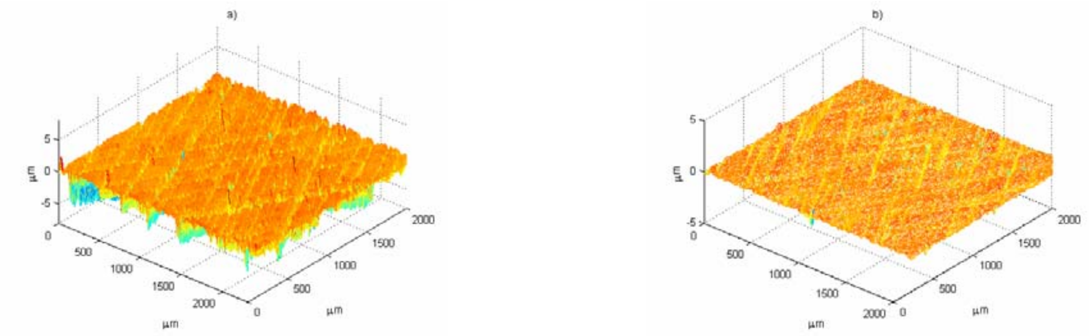
Parameter	Sa	Sq	Sp	Sv	Sz	S10z	Ssk	Sku	Sp/Sz	SHtp	Sdq	Spc	Sdr	Spd	Str	Sal	Std	Sfd
Sa	1	0.942	0.472	-0.196	0.158	0.404	0.775	-0.582	0.723	0.979	0.987	0.956	0.988	-0.956	-0.085	-0.091	0.020	0.759
Sq	-	1	0.661	0.029	0.408	0.645	0.614	-0.453	0.754	0.865	0.933	0.835	0.914	-0.871	0.162	0.114	-0.045	0.553
Sp	-	-	1	0.377	0.823	0.884	0.163	-0.035	0.807	0.358	0.445	0.331	0.404	-0.405	0.490	0.444	-0.322	-0.038
Sv	-	-	-	1	0.837	0.591	-0.644	0.723	-0.182	-0.277	-0.221	-0.264	-0.247	0.238	0.525	0.484	-0.147	-0.573
Sz	-	-	-	-	1	0.885	-0.300	0.425	0.366	0.041	0.126	0.033	0.086	-0.092	0.611	0.560	-0.281	-0.375
S10z	-	-	-	-	-	1	-0.005	0.079	0.579	0.254	0.414	0.247	0.358	-0.330	0.467	0.424	-0.282	-0.180
Ssk	-	-	-	-	-	-	1	-0.908	0.626	0.805	0.774	0.797	0.763	-0.821	-0.319	-0.237	0.134	0.857
Sku	-	-	-	-	-	-	-	1	-0.477	-0.574	-0.613	-0.570	-0.580	0.639	0.444	0.322	-0.160	-0.718
Sp/Sz	-	-	-	-	-	-	-	-	1	0.665	0.711	0.632	0.684	-0.687	0.141	0.128	-0.236	0.430
SHtp	-	-	-	-	-	-	-	-	-	1	0.954	0.982	0.974	-0.951	-0.150	-0.152	0.063	0.818
Sdq	-	-	-	-	-	-	-	-	-	-	1	0.941	0.988	-0.961	-0.156	-0.169	0.011	0.766
Spc	-	-	-	-	-	-	-	-	-	-	-	1	0.960	-0.946	-0.200	-0.195	0.029	0.809
Sdr	-	-	-	-	-	-	-	-	-	-	-	-	1	-0.941	-0.150	-0.173	0.033	0.763
Spd	-	-	-	-	-	-	-	-	-	-	-	-	-	1	0.204	0.230	-0.058	-0.839
Str	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	0.877	-0.085	-0.457
Sal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-0.005	-0.477
Std	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	0.170
Sfd	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1

(b)

Parameter	Sk	Spk	Svk	Smr1	Smr2	Spq	Svq	Smq
Sa	0.943	0.266	0.683	-0.627	0.160	0.280	-0.087	-0.540
Sq	0.819	0.505	0.827	-0.402	0.088	0.487	0.042	-0.407
Sp	0.292	0.692	0.664	0.101	-0.094	0.492	0.273	-0.029
Sv	-0.265	0.436	0.120	0.560	0.062	0.399	0.506	0.068
Sz	0.009	0.675	0.465	0.403	-0.018	0.533	0.472	0.024
S10z	0.188	0.753	0.734	0.167	-0.141	0.502	0.304	0.041
Ssk	0.772	0.037	0.395	-0.749	0.012	-0.009	-0.343	-0.315
Sku	-0.523	0.092	-0.423	0.698	0.165	0.095	0.374	0.037
Sp/Sz	0.588	0.465	0.653	-0.351	-0.140	0.282	0.009	-0.218
SHtp	0.986	0.166	0.522	-0.664	0.270	0.184	-0.147	-0.608
Sdq	0.907	0.248	0.715	-0.666	0.089	0.266	-0.082	-0.493
Spc	0.972	0.169	0.485	-0.650	0.286	0.167	-0.126	-0.586
Sdr	0.942	0.223	0.642	-0.638	0.185	0.223	-0.110	-0.536
Spd	-0.911	-0.179	-0.608	0.700	-0.111	-0.286	0.068	0.500
Str	-0.112	0.746	0.112	0.688	0.157	0.573	0.216	0.056
Sal	-0.118	0.664	0.137	0.533	0.113	0.349	0.154	0.137
Std	0.114	-0.116	-0.125	-0.145	0.051	0.048	-0.237	0.134
Sfd	0.795	-0.225	0.287	-0.846	0.054	0.068	-0.163	-0.488
Sk	1	0.160	0.415	-0.601	0.411	0.174	-0.172	-0.615
Spk	-	1	0.446	0.414	0.002	0.569	0.156	0.080
Svk	-	-	1	-0.334	-0.351	0.443	0.117	-0.102
Smr1	-	-	-	1	0.155	0.228	0.243	0.385
Smr2	-	-	-	-	1	-0.028	-0.176	-0.304
Spq	-	-	-	-	-	1	0.440	-0.025
Svq	-	-	-	-	-	-	1	0.309
Smq	-	-	-	-	-	-	-	1

Imposition method was used during creation of plateau honed cylinder surface. Firstly two crossed textures corresponding to surfaces created by coarse and plateau honing processes, were generated as follows. Two one-directional surfaces oriented in the measurement direction were obtained using the method developed by Wu [10]. These surfaces were rotated by angle Φ equaled to half of honing angle. Next initial one-directional surface was rotated by angle $180^0 - \Phi$ (see [11]). These two oriented surfaces were superimposed and as the results two crossed areal textures corresponding to plateau and valley part were obtained. Sq parameters of these textures were equal to desired values of Spq and Svq parameters of two-process surface. The distance between mean planes of these surfaces was determined in order to obtain desired value of Smq parameter. Then smaller ordinate values of

these two surface topography were selected. The special procedure was used in order to obtain values of other selected parameters describing plateau honed cylinder liner surface topography.
We obtained the following values of confidence intervals of measured surfaces: ±0.164 μm for Sq, ±1.624 μm for S10z, ±0.0115 for Sdq, ±0.0115 for Str, ±0.046^0 for Std, ±0.077 μm for Spq, ±0.621 μm for Svq and ±9.63% for Smq. The parameters Sq, Sdq, Spq, Svq and Smq of modeled surface topographies were correctly matched in 100%, the parameters Str, S10z and Std in 89%. The joint matching condition of all selected parameters was fulfilled in 77% of cases. The relative errors of parameter determination were: for Sq 0.77%, Sdq 5.08%, S10z 9.62%, Str 15.27, Std 1.1^0, Spq 7.09%, Svq 5.1% and Smq 4.25. The relative errors of other parameter determination were studied, too. They amounted: for Sa 9.49%, Sz 11.61%, Sp 12.34%, Sv 10.5%, Ssk 6.45%, Sku 15.32%, Spc 19.12%, Spd 22.525 and Sal 19.32%. Figure 1 presents example of measured and modelled surface. The parameter values are also given.



Sa = 0.55 μm, St = 7.75 μm, Sq = 0.87 μm, Sdq = 0.089, Spq = 0.221 μm, Svq = 2.214 μm, Smq = 76.3%, Sp = 2.5 μm, Sv = 5.25 μm, Ssk = -2.9, Sku = 13.45, S10z = 7.19 μm, Str = 0.047, Std = 26^o, Spc = 0.01, Sal = 0.022 mm

Sa = 0.63 μm, St = 6.75 μm, Sq = 0.89 μm, Sdq = 0.088, Spq = 0.247 μm, Svq = 2.12 μm, Smq = 71.6%, Sp = 2.12 μm, Sv = 4.63 μm, SSk = -2.79, Sku = 13.36, S10z = 6.57 μm, Str = 0.048, Std = 26.5^o, Spc = 0.014, Sal = 0.021 mm

Figure 1. Isometric view of real (a) and modeled (b) cylinder lines surface topography after plateau honing

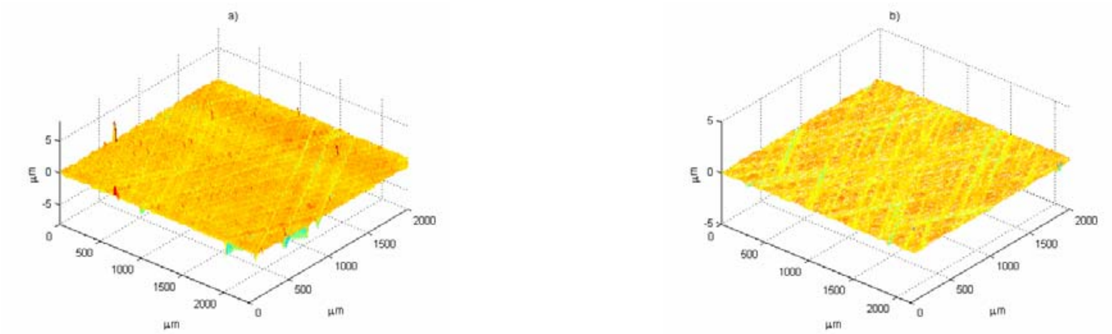
The plateau honing experiment was then carried out using orthogonal selective research plan (see Table 2). Standard deviations of parameters σ, obtained from 6 repetitions are also presented in Table 2. After removal of unsubstantial coefficient the following regression equations were obtained: Sq = 1.19 - 0.036 t, S10z = 11.69 - 0.22 t, Sdq = 0.25 - 0.013 t, Spq = 0.297 - 0.01 t, Svq = 0.44 + 0.094 t, Smq = 38.32 + 3.28 t, Str = 0.03 and Std = 26.5. It is evident that surface topography parameters depended only on plateau honing time t. The standard deviation of surface height Sq and of plateau surface part Spq, slope Sdq and the S10 z parameter was higher for smaller plateau honing time. However values of standard deviation of valley Svq and material ratio Smq were proportional to plateau honing time. The spatial parameters Str and Std were maintained on constant level. For the following machining parameters surface topography coefficients should obtain the following values:

- for p_v = 4.5 MPa, t = 15.3 s: Sq = 0.639 μm, S10z = 8.324 μm, SΔq = 0.0511, Spq = 0.144 μm, Svq = 1.878 μm, Smq = 88.504%, Str = 0.03, Std = 26.5^o,
- for p_v = 5.9 MPa, t = 9 s: Sq = 0.866 μm, Sz = 9.71 μm, SΔq = 0.133, Spq = 0.207 μm, Svq = 1.286 μm, Smq = 67.804%, Str = 0.03, Std = 26.5^o,
- for p_v = 6.4 MPa, t = 16.2 s: Sq = 0.607 μm, Sz = 8.126 μm, SΔq = 0.0394, Spq = 0.135 μm, Svq = 1.963 μm, Smq = 91.456%, Str = 0.03, Std =26.5^o.

Table 2. The effect of plateau honing parameters on areal surface topography parameters

Parameters										
p_v, MPa	**4**	**4**	**4**	**5.2**	**5.2**	**5.2**	**6.4**	**6.4**	**6.4**	**σ**
t, s	**18.9**	**12.6**	**6.3**	**18.9**	**12.6**	**6.3**	**18.9**	**12.6**	**6.3**	
Sq, µm	0.451	0.647	1.109	0.62	0.772	0.911	0.741	0.923	1.171	0.143
S10z, µm	6.193	7.771	9.24	7.501	8.693	10.201	7.547	9.503	10.107	1.412
Sdq,	0.052	0.073	0.126	0.064	0.086	0.101	0.091	0.096	0.107	0.01
Spq, µm	0.141	0.151	0.325	0.155	0.186	0.236	0.142	0.184	0.266	0.067
Svq, µm	2.608	2.215	1.555	1.944	1.778	1.555	3.58	1.723	1.492	0.54
Smq, %	90.027	79.140	34.860	79.697	76.713	53.177	83.300	79.290	40.933	8.38
Str	0.035	0.03	0.032	0.028	0.031	0.032	0.032	0.035	0.027	0.01
Std, ^{0}	26.5	26.5	26.5	26.5	26.5	26.3	26.5	26.5	26.5	0.4

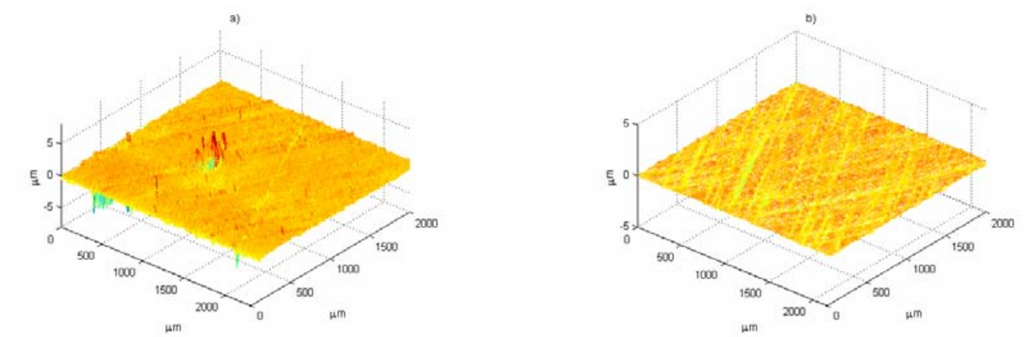
Cylinder surface topographies with these parameters were modeled. We compared the results of simulation with parameters of measured surfaces for plateau honing parameters mentioned above. Matching accuracy of modelled to measured surfaces was fulfilled in 67% of cases. The parameters Svq and Smq of modeled surface topographies were correctly matched in 100%, the parameters Str, Sdq, Spq and Std in 78%, but the parameters Sq and S10z in 89% of all the analysed cases. Figures 2 and 3 present views of representative measured and modeled surfaces for presented above plateau honing process parameters.



Sq = 0.616 µm, S10z = 8.18 µm, Sdq = 0.05, Spq = 0.15 µm, Svq = 1.52 µm, Smq = 94.1%, Str = 0.03, Std = 26^o

Sq = 0.62 µm, S10z = 7.23 µm, Sdq = 0.04, Spq = 0.12 µm, Svq = 1.47 µm, Smq = 90.3%, Str = 0.09, Std = 26.5^o

Figure 2. Isometric view of measured (a) and modeled (b) cylinder lines surface topography after plateau honing for the following machining parameters: p_v = 4.5 MPa, t = 15.3 s



Sq = 0.49 μm, S10z = 7.22 μm, Sdq = 0.045, Spq = 0.14 μm, Svq = 1.8 μm, Smq = 94.1%, Str = 0.06, Std = 26°

Sq = 0.51 μm, S10z = 6.22 μm, Sdq = 0.054, Spq = 0.17 μm, Svq = 1.91 μm, Smq = 91.5%, Str = 0.07, Std = 26.5°

Figure 3. Isometric view of measured (a) and modeled (b) cylinder lines surface topography after plateau honing for the following machining parameters: p_v = 6.4 MPa, t = 16.2 s

4. Conclusions

The following parameters were selected for description of plateau honed cylinder surface topography after plateau honing with stones of ceramic binder: Sq, S10z, Sdq, Spq, Svq, Smq, Str and Std. These parameters were chosen on the basis of their functional performance, the correlation analysis was also helpful in their selection. The modeled surface topographies were correctly matched to measured surface topographies in 77% of all the analyzed cases. The plateau honing experiment was conducted using an orthogonal selective research plan with two machining parameters being input variables: coarse honing pressure p_v and plateau honing time t. Selected previously cylinder liners texture parameters were output values. It was found that plateau honing time was the most important parameter affecting the following surface topography parameters: Sq, S10z, Sdq, Spq, Svq and Smq. The values of spatial parameters Str and Std were constant. The effect of coarse honing pressure on plateau honed surface topography parameters is negligible. It is possible to predict plateau honed cylinder surface profiles when machining parameters are known. Matching accuracy of anticipated to measured surfaces was fulfilled in 67% of all analysed cases.

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